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ELECTRON DRIFT IN PLASMA

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ABSTRACT

A method using two probes for determination of the drift of electrons in plasma was used over a wide range of discharge currents. The circuit was arranged to be sensitive to small changes of the probe current.

1. Introduction

It is known that a series of parameters important for the plasma of gas discharge (electron temperature, electron concentration and electron space potential), is determined with sufficient accuracy for some purposes by means of probes which are introduced into the discharge. /167*

The directional velocity of electrons in plasma carried out with probes by Kovalenko, Rozhanskiy and Sena (ref. 1) has shown that the experimental values for this quantity are only half of those expected.

The analysis of conditions which lead to this result make it possible to develop a method which permits a sufficiently accurate determination of the electron drift in plasma.

In this case we also made two readings with a probe oriented in a special manner. The electron drift in plasma is manifested by the distortion of the probe characteristics.

The asymmetry of probe currents with the working side of the probe facing the anode or the cathode was noticed by Rusk and Peckham (ref. 2) and Oettingen (ref. 3). The initial authors operated under conditions corresponding to processes in the cathode part of the discharge taking place in mercury vapor (low pressure, tube length of 4-5 cm). A second author carried out his measurements in the dark Faraday space and in the strata during discharge in nitrogen.

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*Numbers given in the margin indicate the pagination in the original foreign text.

All of the measurements described in the present article pertain to plasma during discharge in noble gases.

The distortion of probe characteristics in parts of the discharge adjoining the cathode and the determination of the distribution function for fast electrons were recently investigated by Polin and Gvozdover (ref. 4). They used a method for investigating fast electrons which eliminated errors associated with various methods for extrapolating the ion current (ref. 5). The measurements of Rodin (ref. 6) showed that the deviation from the Maxwellian distribution of velocities due to the flows in the cathode parts of the discharge are attenuated at the distance of the mean free electron path λ. If the distribution function for velocities in the cathode parts depends on the coordinate x (ref. 7) (along the axis of the tube), then as transition takes place into the positive column, under the condition $x \gg \lambda$, the distribution function does not necessarily depend on x.

Thus the electron drift in plasma has a constant value along the entire plasma.

The distortion of the probe current in the plasma must therefore not be confused with those deviations from the Maxwellian distribution of velocities which are observed in the cathode parts of the discharge and with the presence of plasma which was first recorded by Langmuir (ref. 8). For an observer who drifts together with the entire flow of electrons towards the anode, the /168 distribution of electron velocities in the plasma appears to be Maxwellian.

The present article describes a sensitive circuit which makes it possible to take into account small current variations at the probe due to the directional velocity of plasma electrons and also due to other reasons, for example, due to charges on walls surrounding the probe or due to charges on another closely situated probe (ref. 9), or due to the presence of impurities in the gas. All of these distortions have been taken into account in our measurements.

It is also of interest to determine the electron drift from the readings of a flat probe, in cases when the plasma is under the action of a magnetic field. The separation of effects produced by the magnetic field both in the plasma and also in the region which is of the order of the mean free path from the probe, becomes possible only when a precise account of electron drift in the discharge is made (ref. 10).

Since in the gas discharge in the plasma we have not only an electron current along the tube which closes the external current circuit, but also a current towards the walls of the tube, the distribution of velocities will be given by the equation

$$f(u,\ v,\ w) = \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\frac{m}{kT}\left[(u-u_0)^2+(v-v_0)^2+(w-w_0)^2\right]}. \qquad (1)$$

If we place the flat probe on the axis of the tube such that the perpendicular to the probe coincides with the tube axis, then v_0 and w_0 become equal to zero (or the radial component of the field along the axis is equal to zero) and the current to the probe depends only on one component of the directional velocity.

If the active side of the probe is turned to face the cathode then the probe current i_k is equal to

$$i_k = Ie^{-\left[(-\eta)^{1/2} - u_0\left(\frac{m}{2kT}\right)^{1/2}\right]^2} + \frac{I_x}{2}\left\{1 - P\left[(\sqrt{\eta}) - u_0\left(\frac{m}{2kT}\right)^{1/2}\right]\right\} \tag{2}$$

when

$$\sqrt{-\eta} > u_0\,(m/2kT)^{1/2},$$

or /169

$$i_k = Ie^{-\left[u_0\left(\frac{m}{2kT}\right)^{1/2} - (-\eta)^{1/2}\right]^2} + \frac{I_x}{2}\left\{1 + P\left[u_0\left(\frac{m}{2kT}\right)^{1/2} - \sqrt{-\eta}\right]\right\} \tag{3}$$

when

$$\sqrt{-\eta} < u_0\,(m/2kT)^{1/2},$$

where

$$P(x) = \frac{2}{\sqrt{\pi}}\int\limits_0^x e^{-y^2}\,dy,$$

and

$$I_x = n\varepsilon u_0.$$

The current on the probe whose active side faces the anode is equal to

$$i_a = Ie^{-\left[(-\eta)^{1/2} + u_0\left(\frac{m}{2kT}\right)^{1/2}\right]^2} - \frac{I_x}{2}\left\{1 - P\left[\sqrt{-\eta} + u_0\left(\frac{m}{2kT}\right)^{1/2}\right]\right\}. \tag{4}$$

Equations (2), (3) and (4) may be generalized for determining

$$I_r = \sqrt{I_y^2 + I_z^2},$$

the directional current to the tube wall by using the general form of the distribution function given by relationship (1).

For a probe situated on the tube axis such that the normal to the probe is perpendicular with respect to the axis, the conventional equations which are derived assuming a Maxwellian distribution of electron velocities, are valid.

By using equations (2), (3) and (4) we can establish the type of distortions which are to be expected when the electron temperature and electron concentration are determined for the case when the semilogarithmic probe characteristics are processed in a conventional manner. Figures 1 and 2 show the theoretical characteristics for a probe whose active side faces the cathode and the anode. The parameter is the ratio of the directional current to the chaotic current. It is interesting to point out that the presence of directional current does not effect the linearity of the characteristics. However, in the first place: the characteristics of figure 1 are displaced up while the characteristics of figure 2 are displaced down with respect to the characteristic of the probe situated parallel to the tube axis ($I_x/i = 0$); in the second place, the slope of the characteristics is changed increasing in figure 1 and decreasing in figure 2 compared with the case $I_a/i = 0$.

The magnitude of I_x/i varies in the limits from zero to unity. When the values of this quantity are high an error can be incurred both in the determination of the temperature and in the determination of the electron concentration by the conventional method which does not take into account the directional current in the plasma.

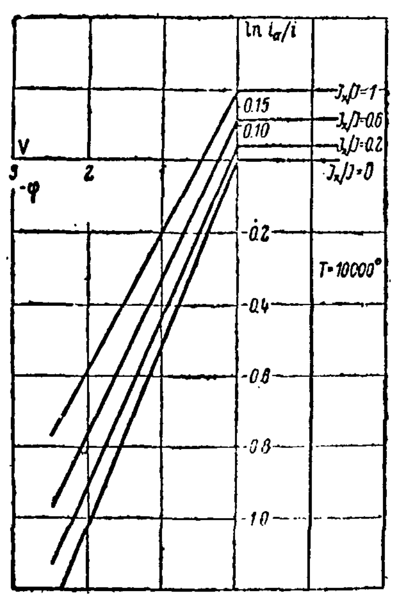

Figure 1

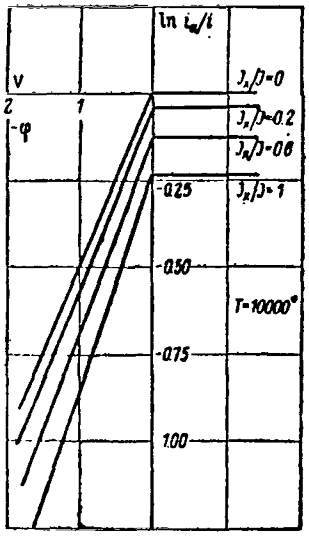

Figure 2

2. Methods and Experimental Results

The investigation of the effect of plane probe rotation on its semilogarithmic characteristics was carried out in argon with an incandescent oxide cathode at a pressure of 0.5 mm (tube No. 1) and 0.9 mm and 1.05 mm Hg (tube No. 2) for different values of the discharge current and for different voltages on the tube electrodes. The oxide cathode was mounted in an open molybdenum cylinder to insulate the walls of the tube from electron flows generated by the cathode. One side of the tube was made sufficiently long (approximately 70 cm) to make the plasma as homogeneous as possible and the other side was made sufficiently wide so that its diameter (4.8 cm) was large compared with the diameter of the plane probe (0.8 cm). This was also done so that the potential of the probe could be looked upon rather definitely as the potential of a given point in the tube space. The plasma contained two plane disc-type /170 probes of the same diameter situated at a distance of 5 cm from each other. One of these Z_2 (fig. 3) was fixed along the axis of the tube parallel to it while the other Z_1 was actuated by the weight of a rod attached to it (brass rod for tube No. 1 and glass rod for tube No. 2) so that its active side would face the cathode or the anode or would be parallel to the tube axis when the discharge tube was rotated. Only one side of each probe was active while the other was protected from plasma currents by a thin layer of mica. During the time of measurement the tube was separated from the vacuum setup (after appropriate cleaning).

The basic electric circuit is shown in figure 3 together with the tube described above and represents a conventional probe scheme. However, a more complicated compensating circuit was used in the operation which made it

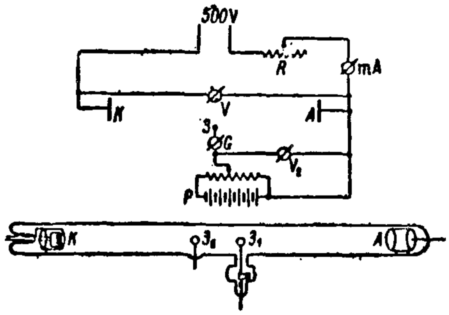

Figure 3

possible to measure quite accurately the variation in the probe currents associated with the rotation of the probe (fig. 4).

This circuit can be applied in cases when it is important to measure small variations in the probe current.

The method of taking measurements by means of this circuit is as follows:

a. During the operation both probes are considered to be at a single point in the plasma. This assumption is valid if the voltage drop in the column between probes Z_1 and Z_2 is compensated by placing a negative potential on probe Z_2 with respect to Z_1 such that the absolute value of this potential is equal to the corresponding potential drop in the column; then the probes will be under identical conditions with respect to the plasma and can be considered as a single probe at a given point in space.

To achieve this, both probes are placed parallel to the tube axis. The negative potential E_1 from the battery is fed to Z_2; the points 1-3, 2-4, and 5-6 are connected; the keys K_2, K_6 are closed (while the keys K_1, K_3, K_4 and K_5 are open). The potentiometer P_2 is set so that the current in device G is equal to zero. The shunt in this case is disconnected (fig. 4).

b. The points 1-3, 2-4 and 5-6 are disconnected; the points 1-2 and 5-7 are connected, the keys K_1 and K_3 are closed. With the given voltage between the anode and probe Z_2 given by the voltmeter V, the corresponding value of the current through Z_2 is recorded (from the reading of G).

c. The same circuit is supplemented by the closing of keys K_4 and K_5 and the source for potentiometer P_3 is used to generate a current in the circuit of

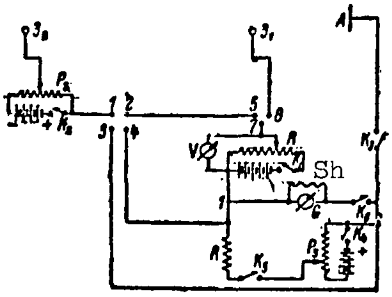

Figure 4

the galvanometer G which is the reverse of the one flowing to Z_2 from the plasma. The potentiometer P_3 is adjusted to reduce the reading of G to zero (R is a resistance of the order of $2 \cdot 10^4$ ohms and is used to prevent the branching of the probe current at point 1).

d. Then Z_1 is turned so that it faces the cathode; the points 5-7 are disconnected and the points 6-7 are connected. Then the device G will give the difference between the currents to Z_1 and Z_2 due to the different positions of these probes with respect to the tube axis (but not with respect to the plasma) thus characterizing the effect of directional electrons flowing to Z_1; the shunt Sh in this case is disconnected. /171

This difference is equivalent to the current difference which would be recorded by G sequentially if we were to place Z_1 parallel to the tube axis and then make it face the cathode. However, the advantage of our method is that a single device can be used to measure the difference of these two currents corresponding to two different positions of the same probe which makes it possible to achieve a high accuracy of measurement. Usually in measuring the total magnitude of the probe current the sensitive galvanometers must have shunts and are incapable of reacting to small current variations.

The same method is used to observe the effect of directional currents associated with the rotation of the probe towards the anode (all of the discussions pertain to probes which are on the axis of the tube).

Figures 5 and 6 show the experimental semilogarithmic characteristics of the probe placed on the axis of the tube parallel to the latter (curve 1) and the corresponding characteristics of the same probe when it faces the cathode (curve 2). The pair of curves in figure 5 were obtained by taking measurements with tube No. 1 when the discharge current was 200 mA. The curve shown in figure 6 pertains to tube No. 2 and a discharge current of 200 mA. A comparison of

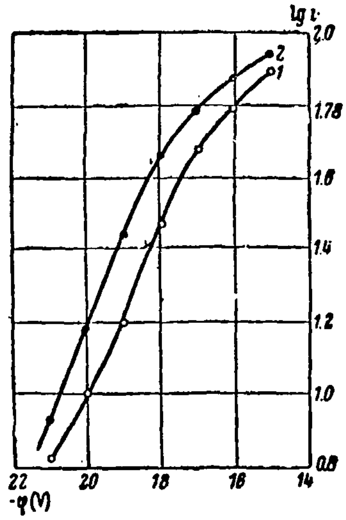

Figure 5

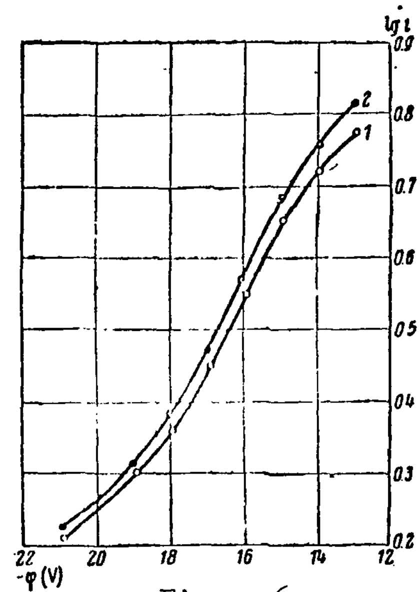

Figure 6

these characteristics with those expected theoretically and shown in figure 1 shows satisfactory agreement between them. The characteristics of the probe facing the cathode 2 always lie above the corresponding characteristics of the same probe when it is placed parallel to the axis (1).

As a matter of fact we should mention that the curves pertaining to tube No. 2, particularly at high currents, exhibit a sharp additional break. This break is observed during all positions of the probe and is associated with the discharge conditions inside the tube. It is obvious that tube No. 2, due to the increased liberation of impurities from the oxide of the cathode, contains a certain quantity of negative ions which fall on the probe in a noticeable amount when the probe potential approaches the space potential. This changes the slope of the characteristics (at the high negative potentials the current of negative ions does not fall on the probe because these ions have low velocities). /172
This explanation is further confirmed by the fact that the curves obtained with tube No. 1 in which the gas was better purified by strong cathode sputtering, do not exhibit such a break (fig. 5).

We should not confuse the breaks which are observed in the semilogarithmic characteristics of the probes placed in the plasma and those placed in the region close to the cathode parts of the discharge. In the latter case the break is due to fast electrons (ref. 8). As shown by Rodin (ref. 6) when the probe is sufficiently removed from the cathode the characteristics with breaks transform into normal characteristics. The breaks in the characteristics observed by us for tube No. 2, when the pressure is sufficiently high and when they are far from the cathode are not due to the directional flows but rather to reasons stated above.

In regard to the characteristics of the probe facing the anode, substantial deviations from theoretical values are observed in some cases. Figure 7 shows the semilogarithmic curves of such a probe when the discharge current is

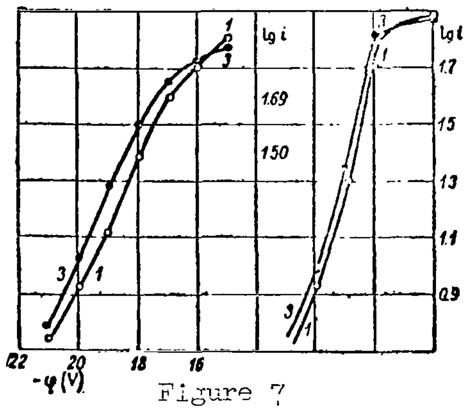

Figure 7

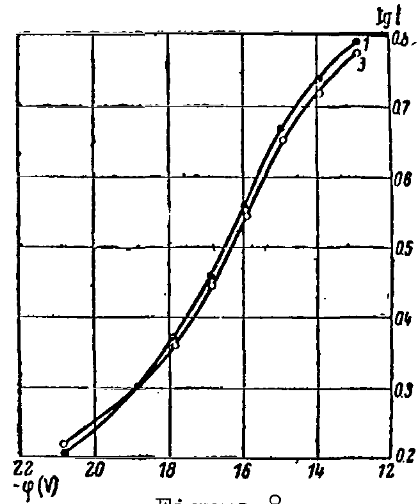

Figure 8

is 200 mA. The left pair is recorded for tube No. 1 and the right pair for tube No. 2. The curves 1 as before refer to a probe which is parallel to the tube axis while curves 3 refer to the same probe when it faces the anode.

As we can see in both cases, characteristics 3 are above 1 and fall below 1 only beyond the space potential. At the same time the corresponding theoretical curves 3 are below curve 1 at all points (fig. 2). For lower discharge currents and higher tube voltages the characteristics of the probe facing the anode are closer to the theoretical values. Thus for the same tube No. 2 when the discharge current is 100 mA curve 3 drops below 1 a few volts before the space potential and when the discharge current is 20 mA, as shown in figure 8, characteristic 3 is below 1 starting at the initial points.

We should note that even if the characteristic of a probe facing the anode lies below the respective characteristics of the probe which is parallel to the axis, this does not always mean that the rotation of the probe towards the anode fails to produce uncontrolled distortion theories. From the theoretical characteristics of currents I_k and I_a must be symmetrically distributed with respect to the semilogarithmic characteristics of the current i, i.e., the following condition must be satisfied

$$i_k - i = i - i_a. \tag{6}$$

Our measurements especially at pressures of 0.9 and 1.05 mm Hg show that the following inequality frequently takes place /173

$$i_k - i > i - i_a,$$

i.e., these two rotations towards the cathode and the anode, are not of equal validity in the sense of observing those conditions which form the basis of the probe theory.

From the entire series of observations described here we can conclude that in some cases the characteristics of probe currents when the probe is rotated towards the anode depart substantially from theoretical ones.

In the case when the probe is rotated towards the cathode the experimental probe characteristics are in agreement with theoretical ones.

If in equations (2), (3) and (4) we let $\eta = 0$ then we can use them to obtain an expression for

$$I_x = i_{k0} - i_{a0}. \tag{5}$$

Equation (5) was proposed in reference 1 for determining the magnitude of the directional current. However, the authors themselves point out that this method gives a value for I_x which is almost half of the expected one (less than the average density of the discharge current in the tube).

The data from our experiments carried out at somewhat higher pressures and over a larger range of discharge currents also show that equation (5) does not give correct values for I_x. Apparently the reason for this is the fact that the rotations of the probe towards the cathode and towards the anode do not follow the same law.

It appears more rational to us to use those quantities for the currents which are in agreement with the theoretical ones. Such quantities are the current I_k and I. Assuming that $\eta = 0$ in equations (2) and (3), we have

$$\begin{gathered} i_k = Ie^{-\frac{m}{2kT}u_0^2} + \frac{I_x}{2}\left[1 + P\left(u_0\sqrt{\frac{m}{2kT}}\right)\right]; \\ I = N\varepsilon\sqrt{kT/2\pi m}, \quad I_x = N\varepsilon u_0. \end{gathered} \tag{7}$$

By using relationships (7) we can find I_x from two readings.

A processing of experimental data by means of equation (7) shows that in this case we obtain values which are close to the expected ones and which are always greater than the average density of the discharge current in the tube.

A series of typical data is shown in table 1. It would appear that the probe characteristics during the rotation of the probe towards the cathode, in spite of the correct position with respect to the characteristics for I, /174
still give a somewhat higher value of the current due to the distortion of the plasma produced by this orientation of the probe.

If we measure the distribution of electron density along the section of the discharge tube we can find the quantity u_0 from equation (11)

$$u_0 = \frac{i}{2\pi\epsilon \int_0^R N r dr}, \tag{8}$$

where i is the current in the external circuit.

A comparison of results obtained by this method of determining u_0 and I_x with the results obtained by a method based on (7) shows good agreement. The discrepancy does not exceed 5-10 percent. This further confirms our proposition that if we know the currents to the probe facing the cathode and facing the tube axis, we can obtain correct results.

The advantage of the method described in the present article is that it requires only two measurements rather than the measurement of the electron density distribution along the entire cross section of the discharge tube. The latter is required when (8) is used.

We should discuss the inaccuracy in determining the space potential and the associated error in the magnitude of electron concentration determined from the value of the probe current i in the presence of space potential. This error is introduced both when relationship (7) is used as well as equation (8).[1] This error can be evaluated by using specific experimental characteristics.

If we use curve 3 of figure 7 (on the right side) to determine the space potential for -4V instead of the assumed value (-6V), the probe current will become equal to 80.6 mA instead of 67.4 mA, i.e., the error in determining the concentration will be only of the order of 10 percent per volt. If instead of the common error of ± 0.5 V we have an error of 2V, the variations in the determination of electron concentration will be from 20-30 percent. However, an error of this order is highly improbable.

TABLE 1

Discharge current mA	I mA/cm^2	I_a $\frac{mA}{cm^2}$ (η = 0)	I_k $\frac{mA}{cm^2}$ (η = 0)	$I_x = I_k - I_a$	I_x average	I_x from (7)	Remarks
200	49.4	52.0	60.0	8.0	11.0	19.0	Tube No. 1
200	128	128.7	136.0	7.3	11.0	16.0	
20	9.2	8.9	9.8	0.9	1.1	1.2	Tube No. 2

[1]We are grateful to L. A. Sena for the discussion of this problem.

As we can see from the characteristics in figure 7 (on the right side) the test conditions which we have selected produce a sharp break in the characteristics during the space potential which decreases the error introduced in the determination of I_x.

The errors in determining the directional velocity may be assumed to be equal to the errors in determining the electron concentration.

3. Conclusions

The experiments described in the present article and their comparison with theoretical data on probes show that:

1. The semilogarithmic characteristics of the electron current flowing to the probe facing the cathode pass above the characteristics of the chaotic current. The linear variation of the characteristics is not disrupted but the slope is somewhat changed. Theoretical and experimental data are in satisfactory agreement.

2. The rotation of the probe towards the anode must lead to the displacement of the same characteristic downward along the axis of the ordinates without a disruption of its linear property. However, in practice this rotation, particularly for high discharge currents, produces a perturbation of the plasma which is not explained by probe theory. This in turn leads to a discrepancy between theoretical and experimental data.

3. The use of equation (5) gives wrong values for the directional current. The use of equation (7) to determine I_x under different discharge conditions produces satisfactory results.

4. The method utilizing equation (7) is controlled by means of equation (8) which serves the same purpose. /175

5. A sensitive circuit has been developed for measuring small variations in probe current by determining the difference in the readings of two probes which are under identical conditions in the discharge.

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